Proposed Voltage Flicker Screening for SIR Screen H

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ITWG Meeting, 1/26/22

Executive Summary

1. Results confirm the <u>SIR screen H was significantly overly conservative</u>. A new screen for flicker is derived with agreement of EPRI, Pterra and Sandia approaches.

2. Proposed new screen is still reasonably conservative. We find that <u>plants sized appropriately for the PCC will pass this screen</u>.

3. Screen is for a single PV plant. Multiple locations <u>reduces cloud variability</u>.

4. Analytical methods used agree with field measured variability data from PV plants. (***includes, worst cast 10-minute, flicker meter, and Sandia method***).

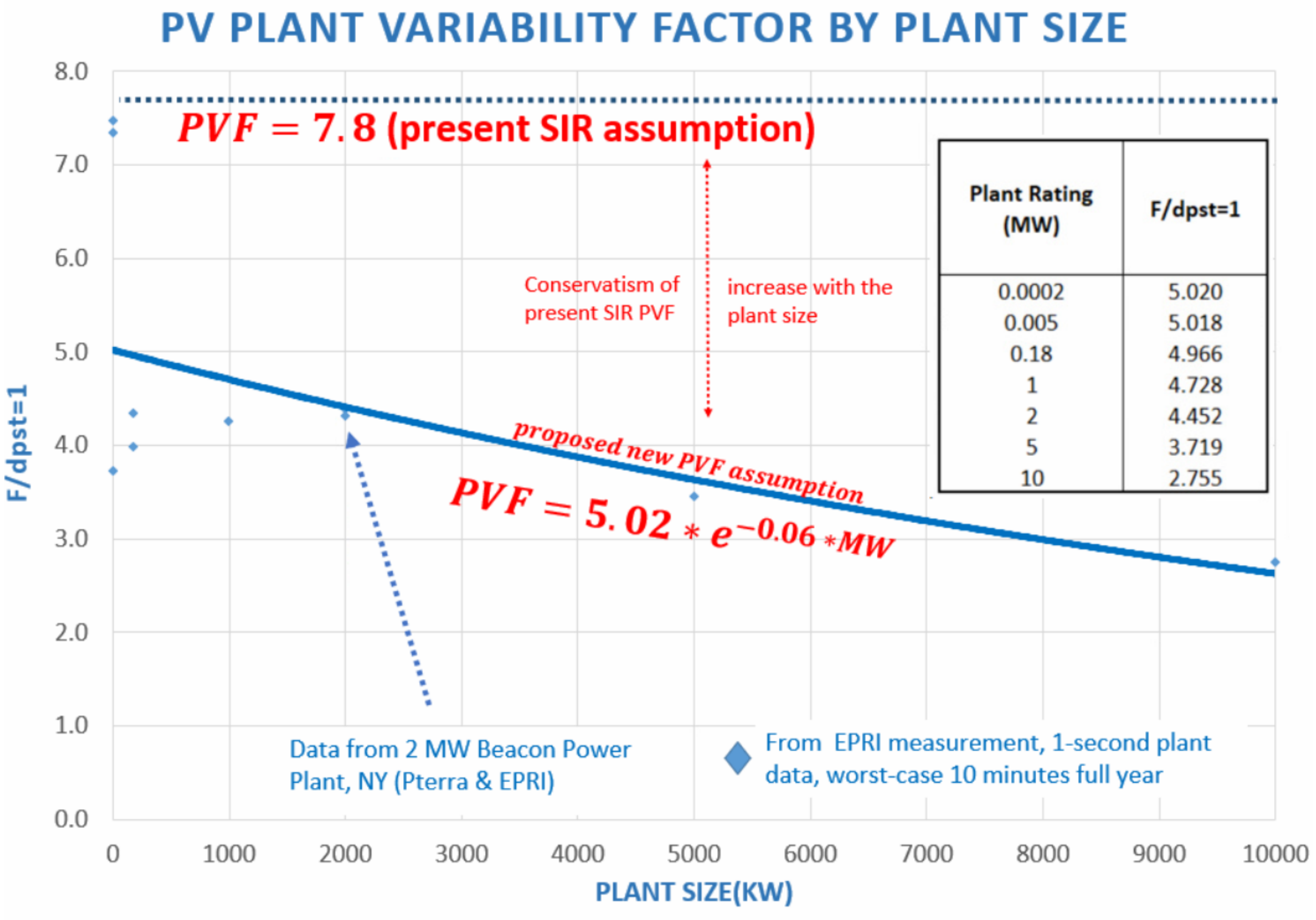
Other Notes:

- IEEE 1547-2018 flicker allocation is used in this analysis.
- Larger PV plants have less output variability. Point solar irradiation measurements show high variability that may be misleading.
- Site flicker measurements include load variability, not limited to Pst <.35

Objectives

- NYSERDA/DPS requested EPRI and Pterra to complete the following scope of works
  1. Converge on a single jointly endorsed formula for flicker screen (SIR Screen H)
  2. Supply the model verification of the new, jointly endorsed flicker test calculation, including inputs, outputs, and any assumptions made
  3. Show how modeling outputs from the new, jointly endorsed equation(s) correlate to flicker reading from real-world projects
  4. Supply key assumptions and standard methodology to perform Time-series simulations (TSS)
  5. Verify if the proposed screening formula is sufficiently conservative and more conservative than the results from time-series simulations and measurements

Recommendation – Proposed New PVF Assumption Equation



Plant Rating (MW)	F/dpst=1
0.0002	5.020
0.005	5.018
0.18	4.966
1	4.728
2	4.452
5	3.719
10	2.755

- PVF = PV plant variability factor
- PVF or F/dpst=1

Present SIR assumption

$$PVF = \frac{F}{d_{pst=1}} = 7.8$$

Proposed PVF assumption

$$PVF = 5.02 * e^{-0.06*MW}$$

Recommendation– Proposed Screening Flicker Update

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SIR

Conservative Assumption

$$P_{st} = d \times 7.8$$

$$P_{st} = d \times \frac{F}{d_{pst=1}}$$

$$P_{st} = d \times \frac{0.2}{2.56\%}$$

$$P_{st} < 0.35$$

Proposed

Still maintain conservatism

$\frac{F}{d_{pst=1}}$ →

- Will change based on solar plant capacity (P) in MW
- Based on 1-second measurement data, worst-case 10 minutes
- Consistent with WVM simulations ~ Represent geographic smoothing of PV power output

$$P_{st} = d \times 5.02\, e^{-0.06 \times MW}$$

Retain equation from SIR based on POI strength/stiffness (MVAsc and X/R) – obtained from Screen F

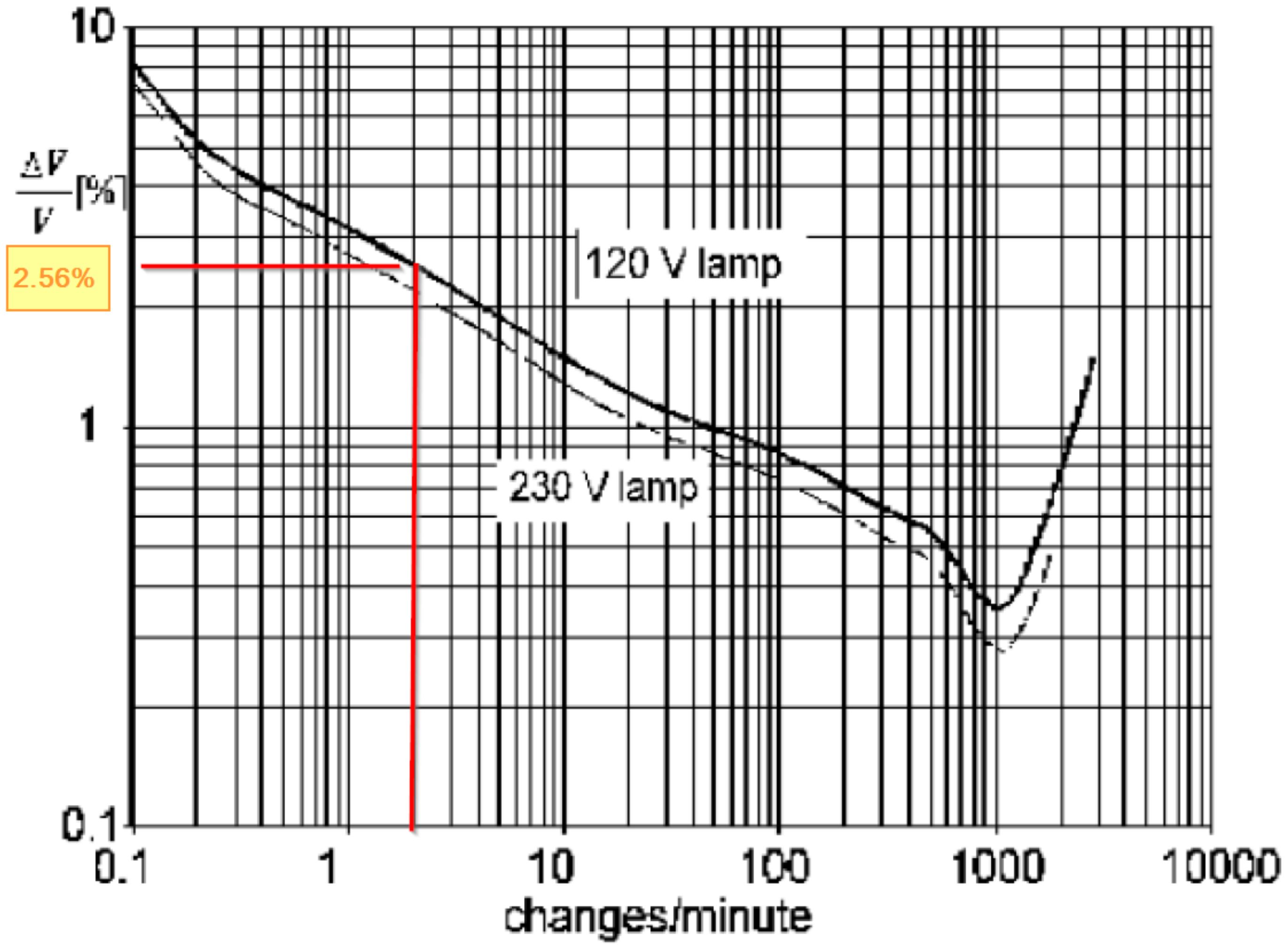
Pst Limit – IEEE1453 and Conservative Assumptions

$$P_{st} = \left(\frac{d}{d_{pst=1}}\right) \times F$$

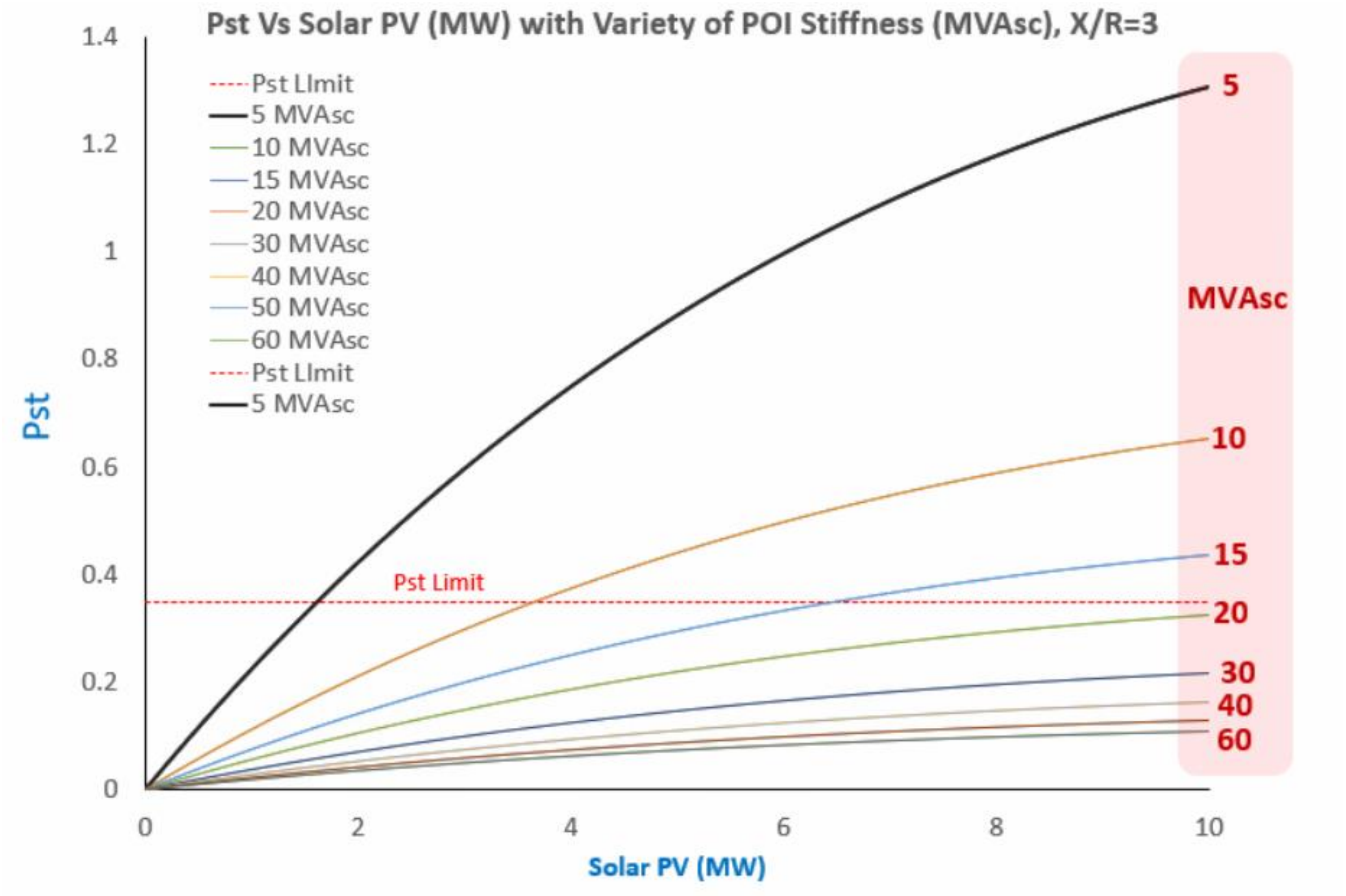
$$P_{st} = \left(\frac{d}{2.56\%}\right) \times 0.2$$

$$P_{st} = d \times 7.8$$

$d_{pst=1}$ is the relative voltage change that yield P_{st} value of unity assuming rectangular voltage fluctuation (2.56% assuming 1 dip/minute or 2 changes/minute)



Recommendation – Proposed New PVF Assumption & Flicker Screening Equation



- The weaker the POI (lower MVAsc), the higher the impact on the Pst or ΔV
- With weak POI of 10 MVAsc the 3.8 MW PV project could fail the flicker screening but other issues will appear before the flicker (ANSI voltage violation, voltage fluctuation, voltage regulator variation test)
- ΔV at the POI < 6.9 % will not cause the flicker issue but could trigger voltage fluctuation issue

Pst Limit & Voltage Change Limit

$$P_{st} = \left(\frac{d}{d_{pst=1}}\right) \times F$$

Pst limit = 0.35 based on IEEE Std. 1547 - 2018

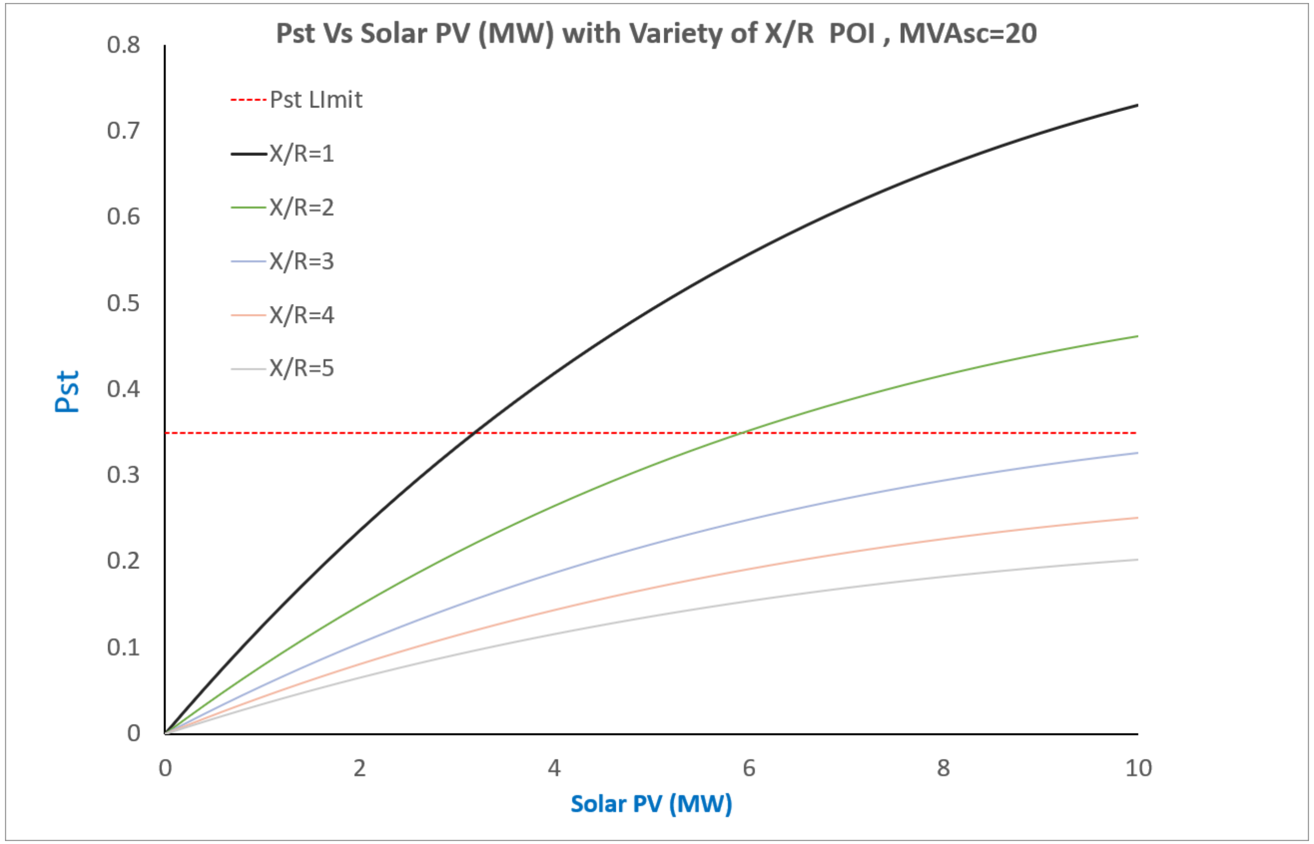
$$d = \frac{P_{st}}{\frac{F}{d_{pst=1}}} = \frac{0.35}{5.02 \ * \ e^{-0.06*MW}}$$

For the worst-case:
assume very small PV Plant 1 KW

$$d < 6.9\%$$

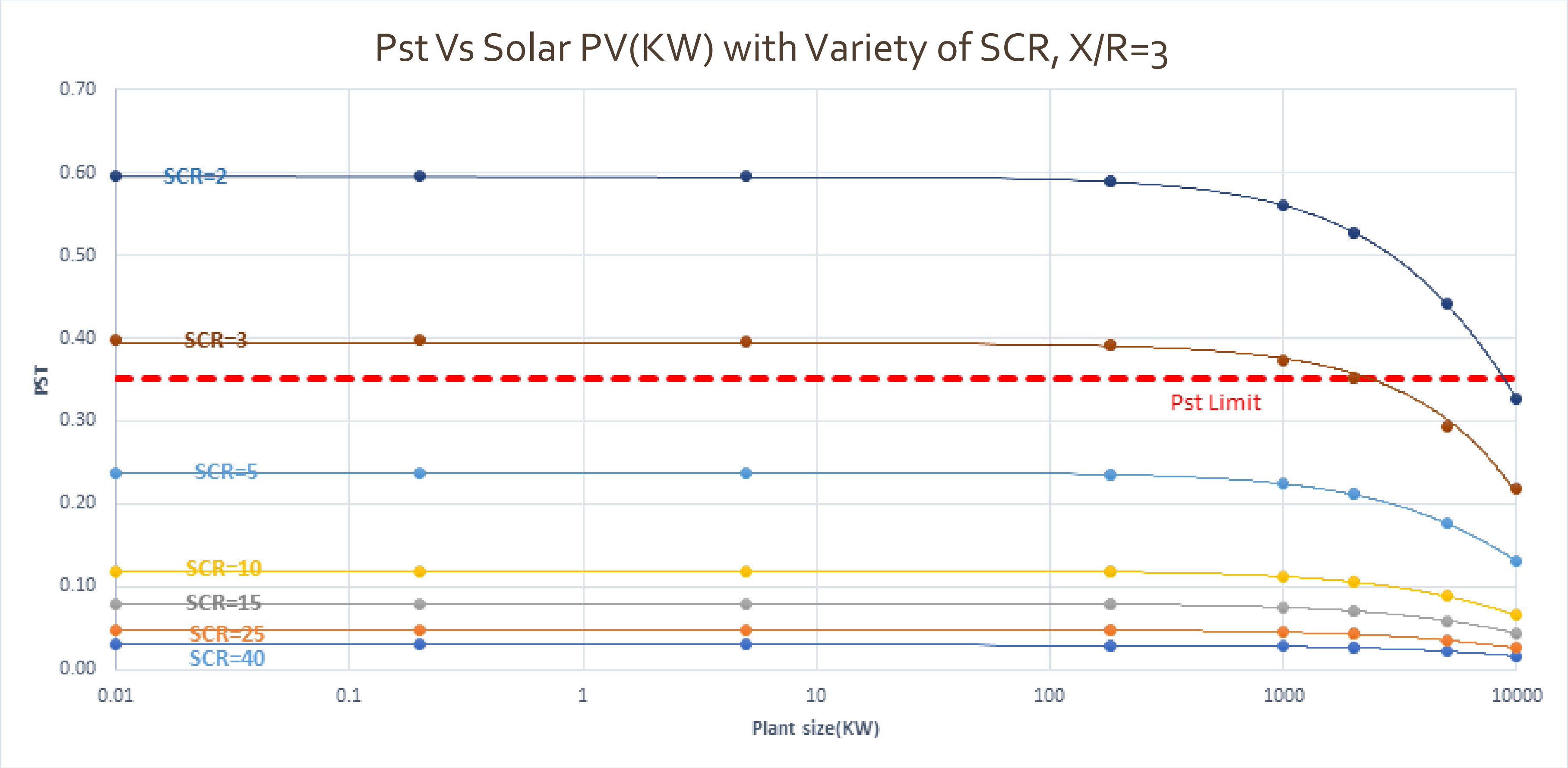
Voltage change should be less than 6.9 %

X/R Ratio Impact on Pst

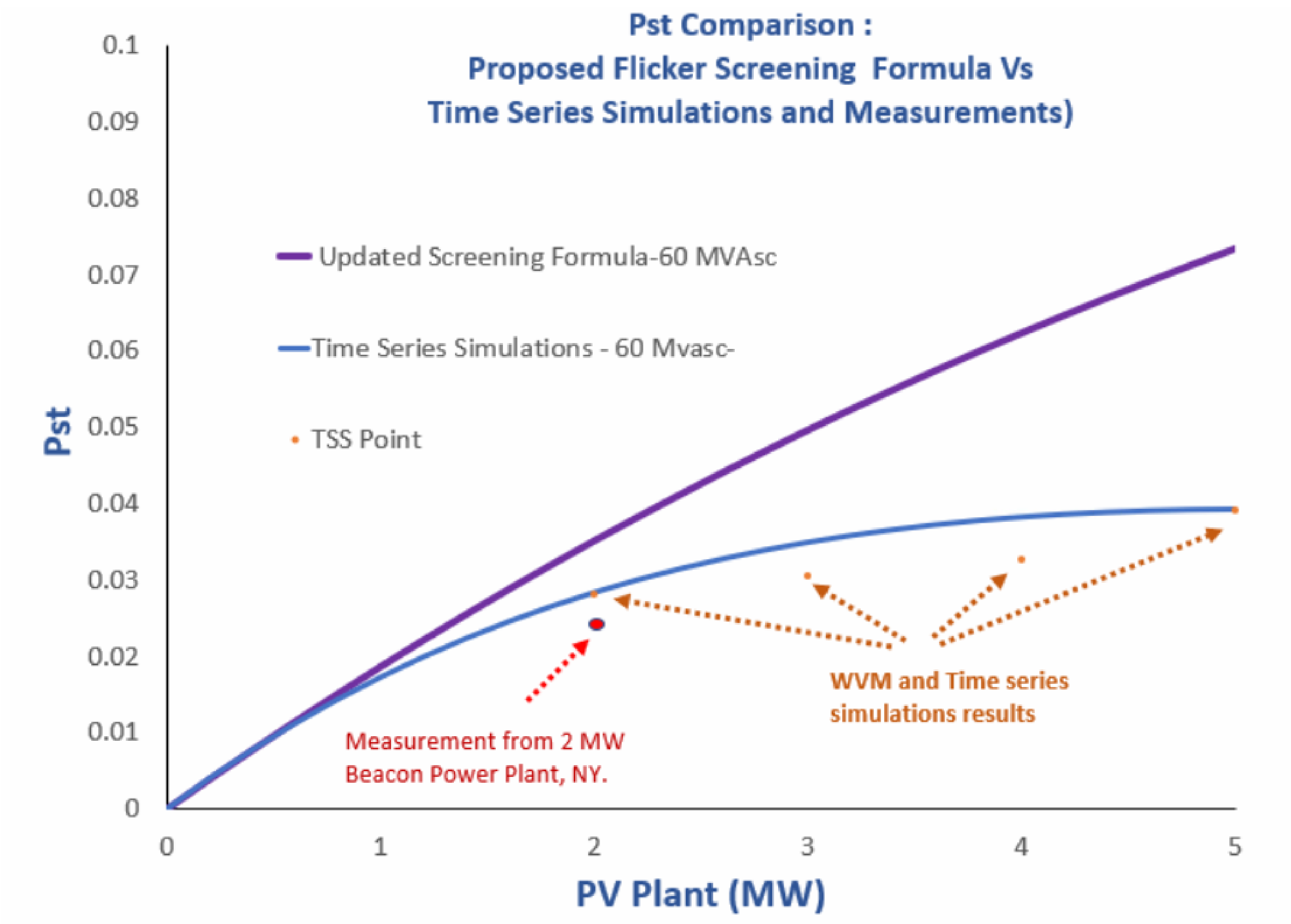


- The lower the X/R ratio at the POI, the higher the impact on the Pst

Recommendation – Proposed New PVF Assumption & Flicker Screening Equation

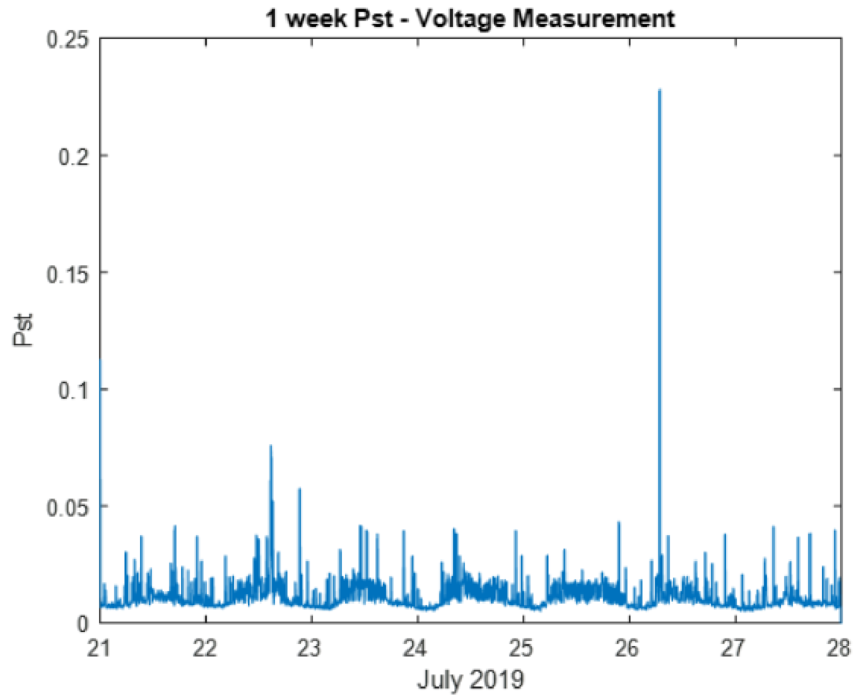


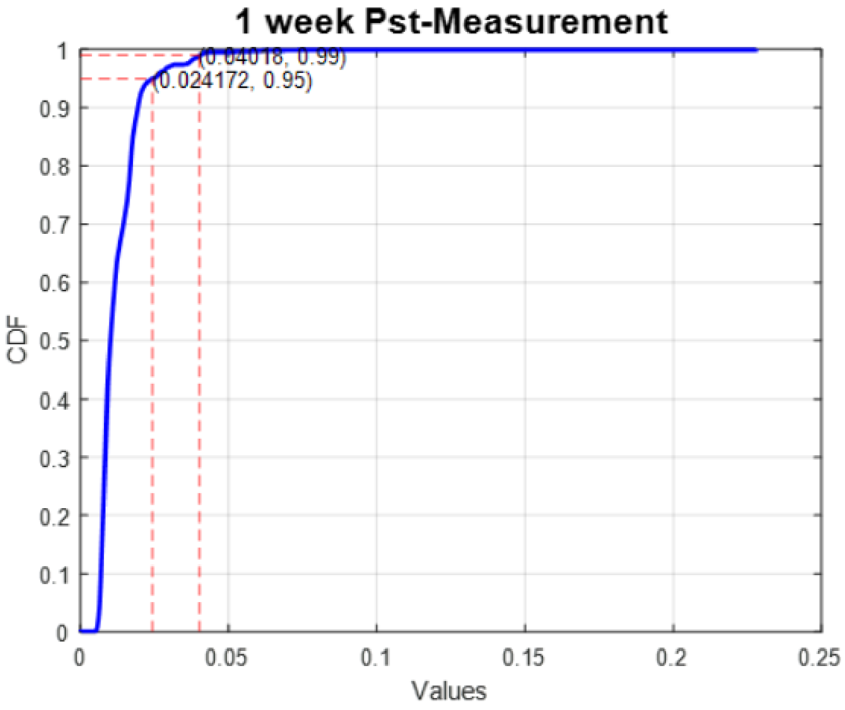
Pst Comparison – Proposed Flicker Screening Equation Vs Time Series Simulations Vs Measurement



- **Screening >> TSS >> Measurement**
- Proposed flicker screening is sufficiently conservative, it is more conservative than time-series simulations and the Pst measurements
- Time series simulations based on 95% percentile of 1-week simulations Vs the worst 10 minutes in flicker screening
- Pst calculation using screening formula assumes a very conservative & static ΔP of 75%
  - The worst 10 minutes from measurement show ΔP of less than 30%, 1-week shows ΔP of less than 10% (95 percentile)

Pst Comparison – Proposed Flicker Screening Equation Vs Time Series Simulations Vs Measurement





Example

5 MVA PV Project with unity power factor (PF=1) is connected to 13.2 kV circuit where short circuit at POI is 30 MVA and X/R ratio of 3.75

```
2. Bus Fault on:          0 Project1     13.2 kV 3LG
                                                   FAULT CURRENT (A @ DEG)
         + SEQ                - SEQ              0 SEQ           A PHASE          B PHASE          C PHASE
       1312.1@ -75.1        0.0@    0.0        0.0@    0.0     1312.1@ -75.1    1312.1@ 164.9    1312.1@  44.9
                                                   THEVENIN IMPEDANCE (OHM)
      1.50003+j5.61789   1.50003+j5.61789   1.50003+j5.61789

         SHORT CIRCUIT MVA= 30.0            X/R RATIO= 3.74519      R0/X1= 0.26701    X0/X1= 1.
```

$$d = \left(\frac{R_L \times \Delta P + X_L \Delta Q}{V_r^2} \right)$$

With MVAsc and X/R ratio known, RL and XL can be calculated (1.5 + J5.6 Ohm)

Voltage change d = (75%*5*1.5)/13.2^2 = 0.032 (3.2% or less than 4.48%)

$$P_{st} = d \times 5.02\, e^{-0.06 \times MW} = 0.032 \times 5.02\, e^{-0.06 \times 5\, MW} = 0.12$$

Evaluating the Impact of Multiple PV – General Summation Law

A general combination relationship for short-term flicker severity caused by various installations has been found in the following form, where P_{st} are the various individual levels of flicker severity to be combined:

$$P_{st} = \sqrt[\alpha]{\sum_i P_{st_i}^{\alpha}}$$

NOTE The same equation can be used for the long term flicker index P_{st}

Where :

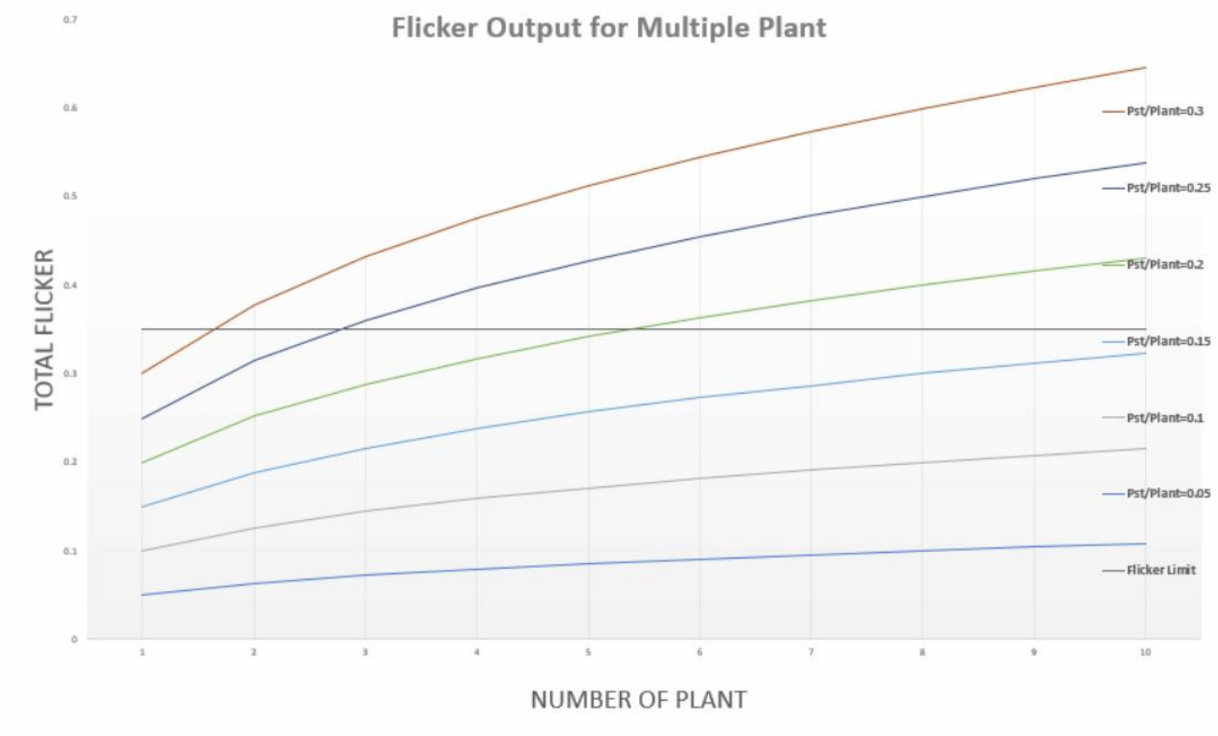
- P_{st} is the magnitude of the resulting short term flicker level for the considered aggregation of flicker sources (probabilistic value),
- α is an exponent that depends on various factors discussed below
- $P_{st_i}^{\alpha}$ is the magnitude of the various flicker sources or emission levels to be combined,

In general, a value of α= 3 ("cubic summation law") has been largely used for years and is recommended for P_{st} (or P_{lt}) summation provided that additional information is not available to justify a different value.

See Annex D of IEEE-1453 for a discussion of an equivalents severity factor which may simplify the calculations in some cases.

Evaluating the Impact of Multiple PV – General Summation Law

	PST									
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Pst/Plant=0.05	0.050	0.063	0.072	0.079	0.085	0.091	0.096	0.100	0.104	0.108
Pst/Plant=0.1	0.100	0.126	0.144	0.159	0.171	0.182	0.191	0.200	0.208	0.215
Pst/Plant=0.15	0.150	0.189	0.216	0.238	0.256	0.273	0.287	0.300	0.312	0.323
Pst/Plant=0.2	0.200	0.252	0.288	0.317	0.342	0.363	0.383	0.400	0.416	0.431
Pst/Plant=0.25	0.250	0.315	0.361	0.397	0.427	0.454	0.478	0.500	0.520	0.539
Pst/Plant=0.3	0.300	0.378	0.433	0.476	0.513	0.545	0.574	0.600	0.624	0.646



Assumption:

$\alpha = 3$

Example: Five PV projects with sizes ranging from 0.5 to 5 MW connected to the same circuit with a variety of stiffness at the POI ranging from 5 MVAsc – 30 MVAsc. Calculate Pst for the fifth project.

Project Sequence	Size (MW)	MVASsc @ POI	X/R	Pst (based on EPRI V9+Pterra gaussian)	Pst General Summation Law	Number of PV on the Circuit
1st Project	5	30	3	0.147	0.147	1
2nd Project	0.5	5	1.5	0.203	0.226	2
3rd Project	2	15	2.5	0.165	0.252	3
4th Project	1	10	2	0.159	0.272	4
5th Project	3	20	2.75	0.161	0.289	5

Evaluating the Impact of Multiple PV – What Limit to Use for multiple PV units?

IEEE-1547 indicates that if an individual plant has Pst <0.35, the plant is considered a non-fluctuating facility.
Thus, modeling an individual plant for each circuit is sufficient for the development of the flicker screening equation.

7.2.3 Flicker

The DER contribution (emission values) to the flicker, measured at the PCC, shall not exceed the greater of the limits listed in Table 25 and the individual emission limits defined by IEC/TR 61000-3-7. Any exception to the limits shall be approved by the Area EPS operator with consideration of other sources of flicker within the Area EPS.

Table 25—Minimum individual DER flicker emission limits[a]

E_{Pst}	E_{Plt}
0.35	0.25

[a]95% probability value should not exceed the emission limit based on a one week measurement period.

Assessment and measurement methods for flicker are defined in IEEE Std 1453 and IEC/TR 61000-3-7. In addition, the following shall apply:

— Equipment other than a DER shall be allowed to mitigate the flicker induced by a DER.

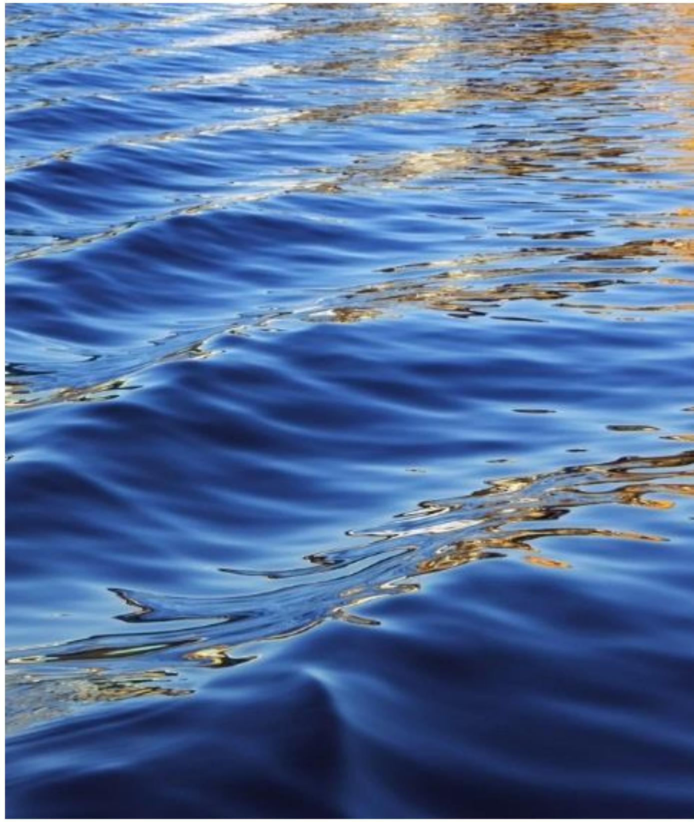
— E_{Pst} is the emission limit for the short-term flicker severity, P_{st} If not specified differently, the P_{st} evaluation time is 600 s.

IEEE-1453 considered the Pst level after allowing for flicker that propagates from other locations, it has criteria which is much higher (Pst=0.9 Vs 0.35) than the one defined in IEEE-1547: Based on IEEE Std. 1453, the planning levels recommended for POIs at MV, HV, and EHV systems are shown in Table 2-1. The planning levels are developed to be the basis for applying emission limits for individual customers with POI at these different voltages. The individual customer emission limits are developed using a procedure that allots each customer some portion of a planning level after allowing for flicker that propagates from other locations.

IEEE 1453 Recommended Flicker Limit			
	Planning Level for Proposed Fluctuating Installation (Project) 95% Probability Level for a full week evaluation		Compatibility Level Existing Installation 95% Probability Level
	MV (>1kv & <=35 kv)	HV-EHV (>35kv)	LV(<= 1kv)
Pst	**0.9**	0.8	1
Plt	**0.7**	0.6	0.8

Sandia in its Flicker PV Project study use the limit from IEEE-1453

Supporting Material



Time Series Simulations Overview

<u>What is TSS?</u>

Cover and include time-dependent aspects of power flow, including the interaction between the daily changes in load and PV output and control actions by feeder devices

<u>*Why do we need TSS?*</u>

- PV output is highly variable and the potential interaction with control systems may not be adequately analyzed with traditional snapshot tools
- Many potential impacts, like the magnitude and frequency of voltage variation cannot be accurately analyzed without it

<u>*What are the issues with utilizing snapshot steady-state tools?*</u>

- Snapshot analyses that only investigate specific time periods can be overly pessimistic about PV impacts because it does not include the geographic and temporal diversity in PV production and load

Time Series Simulations Overview

<u>TSS requirement</u>

- Require high-resolution input data
- Require new tools or purchase a new module
- Open-source tool is available (Open DSS) but requires new experience and scripting/coding skills to automate the process

Time Series Simulations Methodologies

Tools : OpenDSS, SANDIA WVM, MATLAB, Milsoft

1. Convert the base case from Milsoft to OpenDSS, perform verification to ensure both cases closely match

2. SANDIA WVM Tool (require MATLAB)
   a) From a single irradiance data (preferably 1-second resolution), prepare the MW output of the project for at least 1-week period using Sandia WVM Tool
   b) The code syntax, required input, and application example are available from the following link

   https://pvpmc.sandia.gov/applications/wavelet-variability-model/

   - For this project, we use single irradiance data from Beacon Power Plant and its Milsoft circuit database from CHGE

Time Series Simulations Methodologies

3. OpenDSS – refine the base case model
   a) Include the PV plant model from 2a to OpenDSS model
   b) Include load profile data into the model. One hour data can be linearly interpolated to represent 1-second data
   c) Refine the voltage regulator model to include time delay setting

4. OpenDSS – perform time-series simulations
   a) Perform time-series simulations for at least 1 week and obtain Pst values
   b) Obtain Pst 95 percentile and compare it against the criteria defined in IEEE-1453

Note: there has been discussion in the OpenDSS forum that Pst calculation in OpenDSS would produce less accurate Pst because there could be an error with approximating the time domain waveform from RMS solutions. It will assume the voltage is constant for 1 s. Pterra uses MATLAB flicker meter tool to produce the Pst values from OpenDSS voltage outputs. Please refer to the flicker meter section.

Time Series Simulations Methodologies

Pterra performed the following tasks for this project that may not be needed for time-series simulations in the CESIR process:

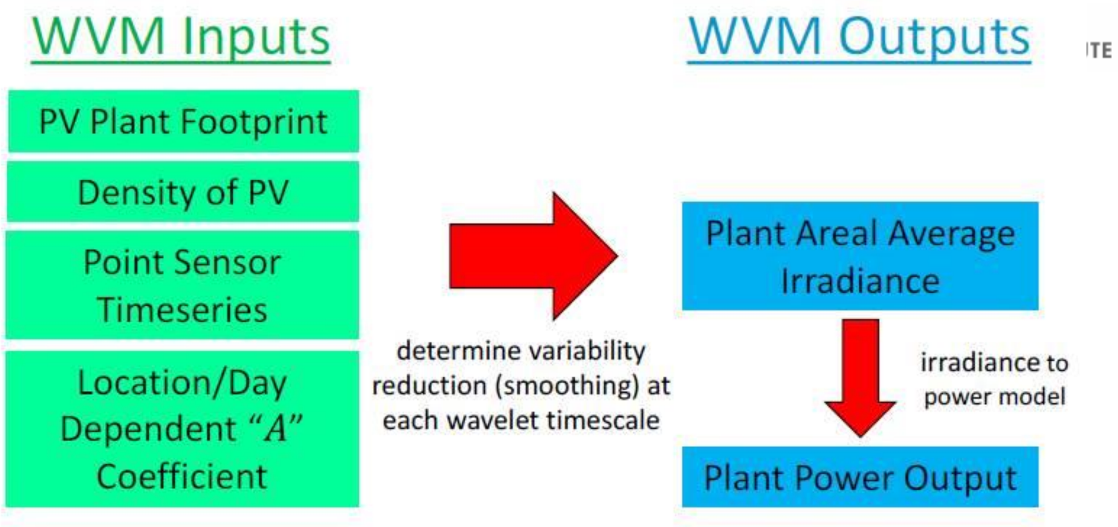
- Benchmarking: Compare WVM output from single irradiance sensor Vs Measurement
- Based on the WVM model, change the plant output from 2 MW to 3 MW, 4 MW, and 5 MW
  - Determine the Pst for different PV outputs (2MW – 5 MW)

Time Series Simulations Assumptions

- Hourly load profiles were transferred to a 1-second load profile using linear interpolation
- Time-series simulations were performed with 1-second resolution
- Voltage regulation time delay is modeled according to the settings provided by CHGE

WVM Simulations

Reference: A wavelet-based variability model (WVM) for Solar PV Power Plant, Matthew Lave, Jan Kleissl, Joshua S. Stein



- WVM (wavelet variability model) create PV plant output from a single point sensor.
- Obtain the variability of a potential power plant (i.e. largest ramp rates and how often they occur)

Lave et al. A Wavelet-based Variability Model (WVM) for Solar PV Powerplants 6

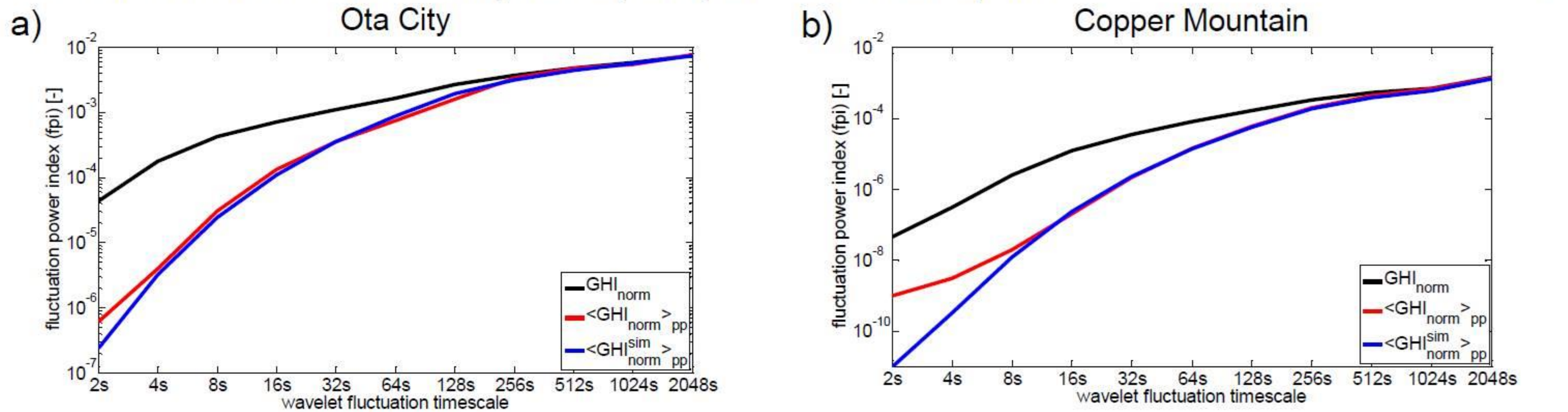
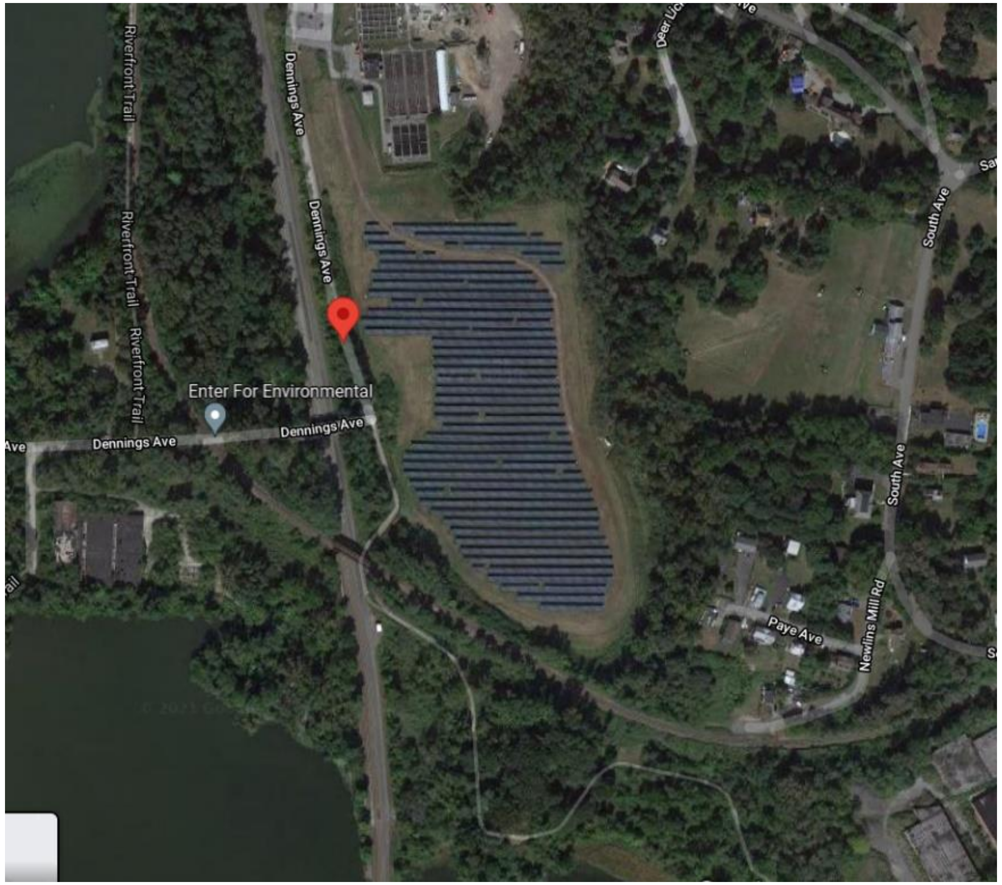


Fig. 6. Fluctuation power index (fpi) for the GHI point sensor (black), actual power output of (red), and simulated power output (blue line) at (a) Ota City on October 12, 2007 and (b) Copper Mountain on October 1, 2011.

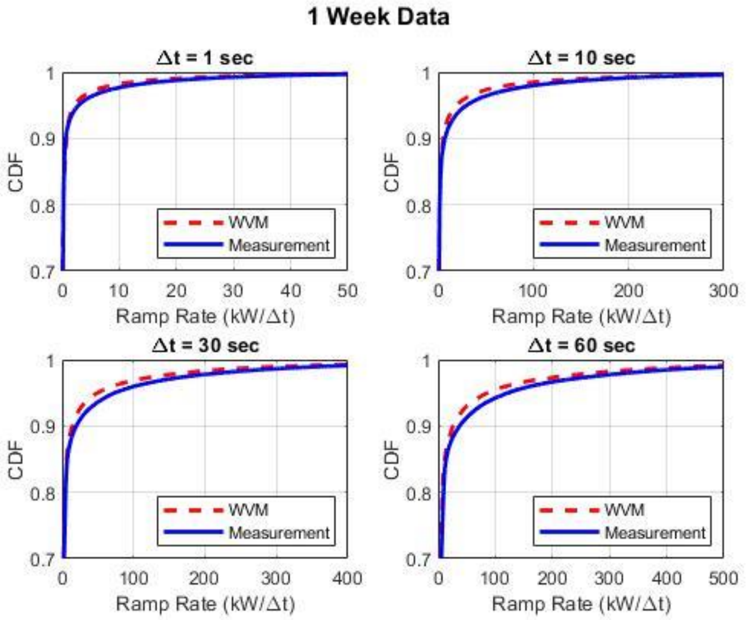
Benchmarking WVM Approach and Measurement
2 MW PV Plant, Beacon, NY

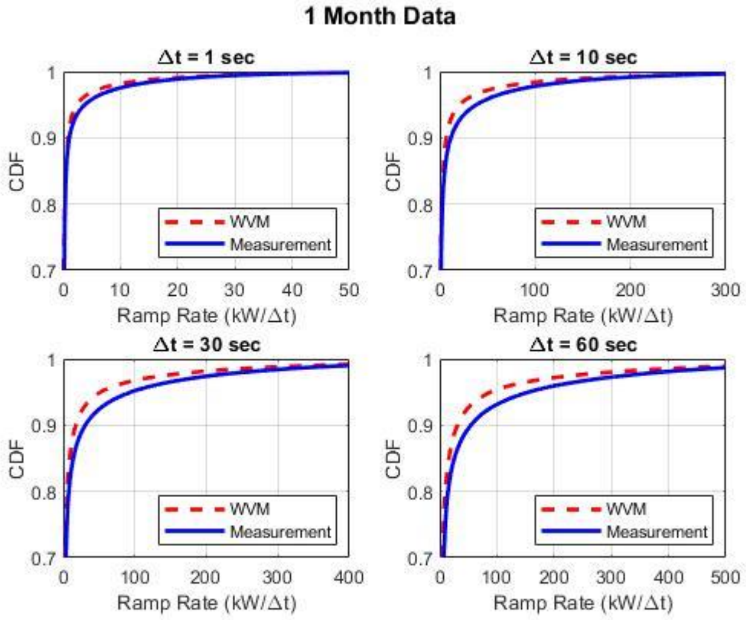


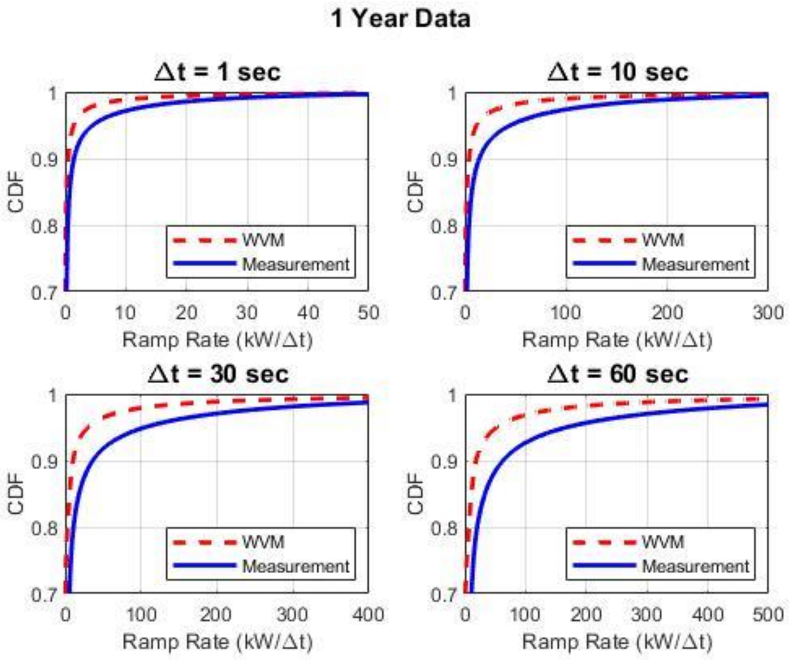
Location: 100 Dennings Avenue, Beacon, NY 12508
[41°29'30.9"N 73°58'53.3"W - Google Maps]
Single irradiance data: 1 second
Power, Voltage output at POI:
Interconnection to 13.2 kV System, 4 wire Y multi-grounded,
About 2.5 miles from Substation (3 winding, 12/16/20 MVA), Load (1.5 – 3.5 MW)

Ramp Rate Distribution WVM Versus Measurement
2 MW Beacon PV Plant, NY

Ramp rate for actual power output from measurement (blue) Vs. simulated power output (red)





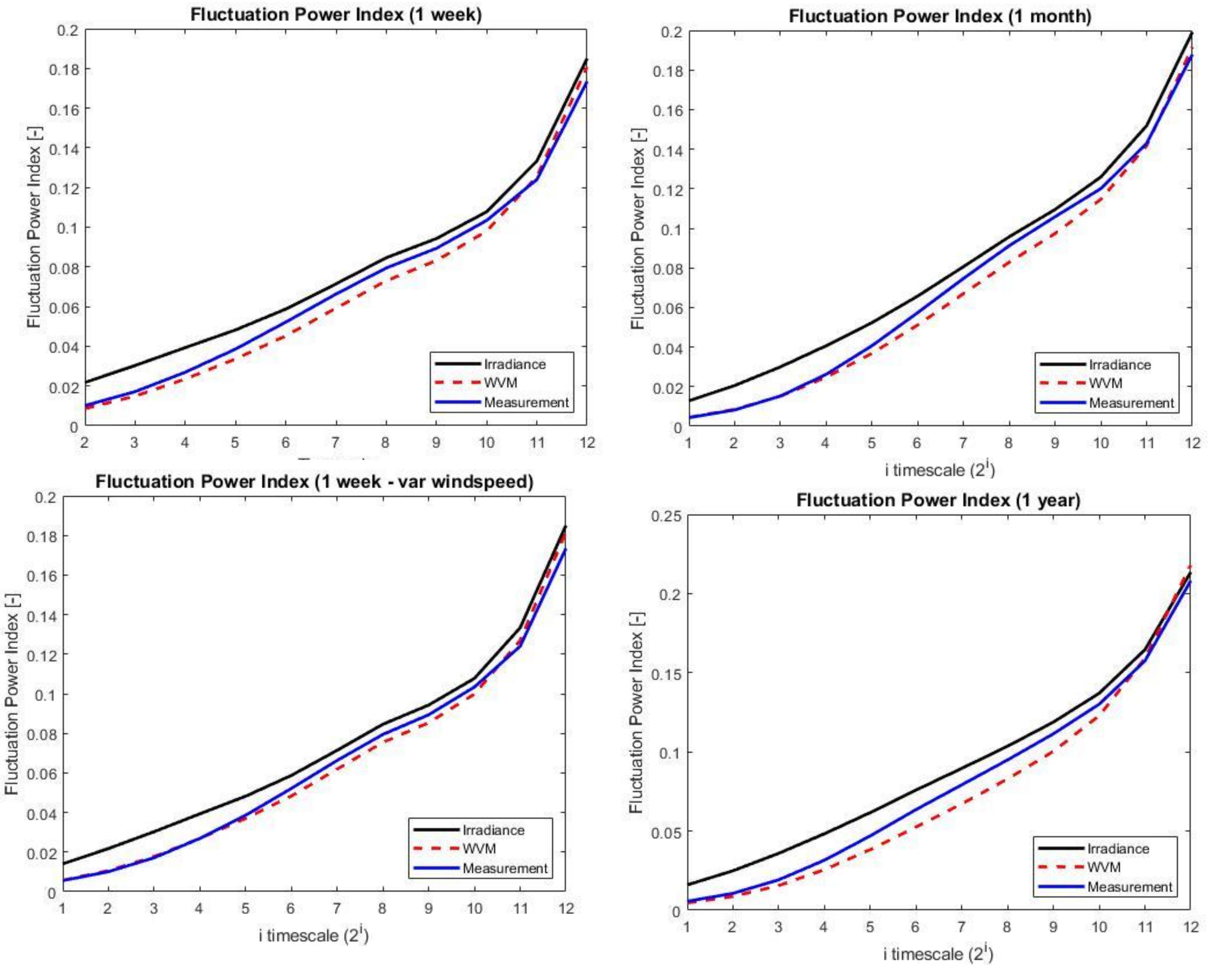


- Simulated power outputs from single irradiance data (red) closely match or are slightly more conservative than actual power output from measurement (blue)

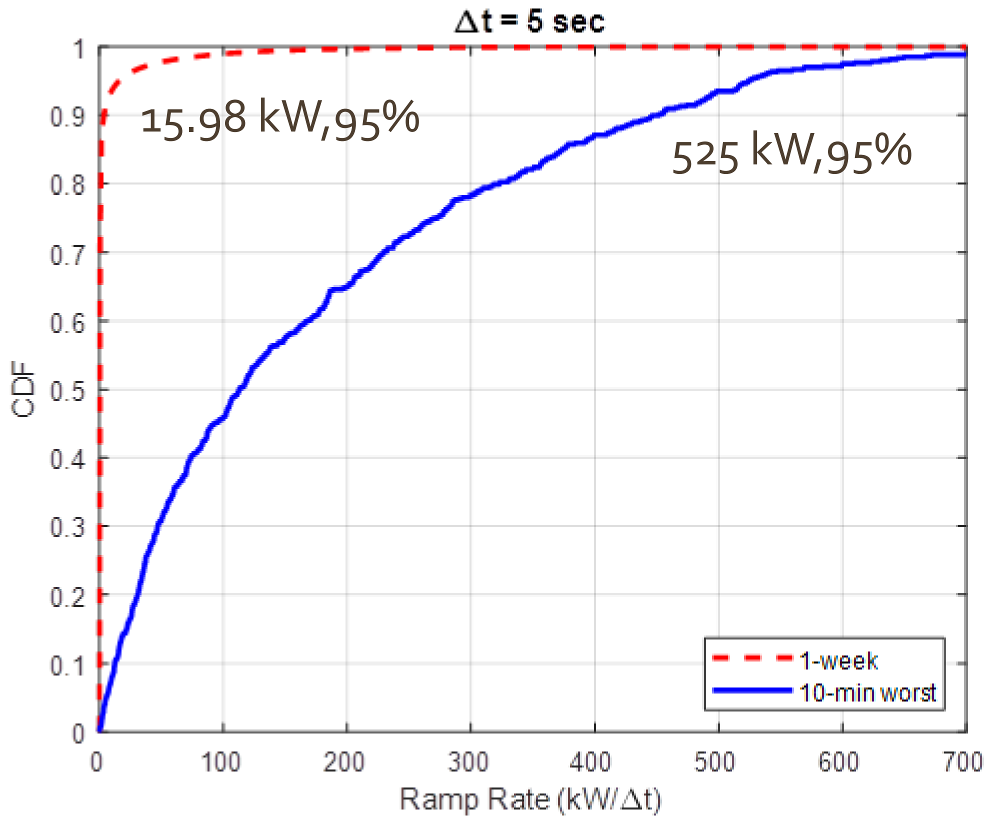
Fluctuation Power Index WVM Vs Measurement
2 MW Beacon PV Plant, NY

Fluctuation Power Index (FPI) for actual power output from measurement (blue) Vs. simulated power output (red) and single irradiance data (black)

- With a small time-scale, FPI for actual power output from measurement (blue) Vs. simulated power output (red) match closely
- FPI for single irradiance data (black) shows consistently much higher FPI, demonstrating data from single irradiance data should not be used for big PV units. Geographic smoothing should be taken into account



Ramp Rate Comparison – Understanding the Conservatism between Flicker Screening and Actual Data from Measurement



- Use measurement data from Beacon Power Plant
- Ramp rate for 1 week, 95% percentile is about 16 kW (or less than 1% of its nominal rating)
- Ramp rate for the worst 10-minute, 95% percentile is about 525 kW (or about 26% of its nominal rating)

Shape Factor Approach Review

- 63 changes/10 minutes ~ 6.3 changes/minute
  - Use MATLAB extrapolation methods for fluctuation less than 10 changes/minute, F = 0.07

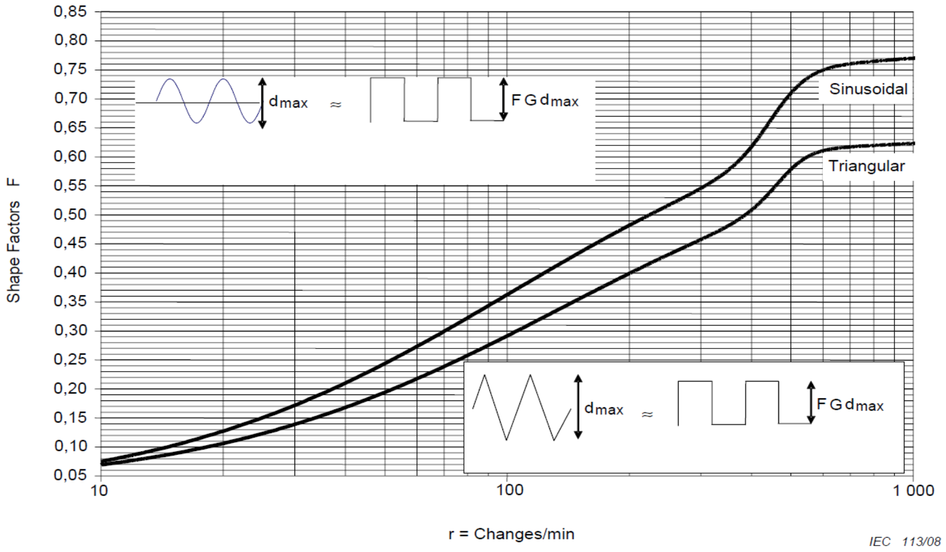
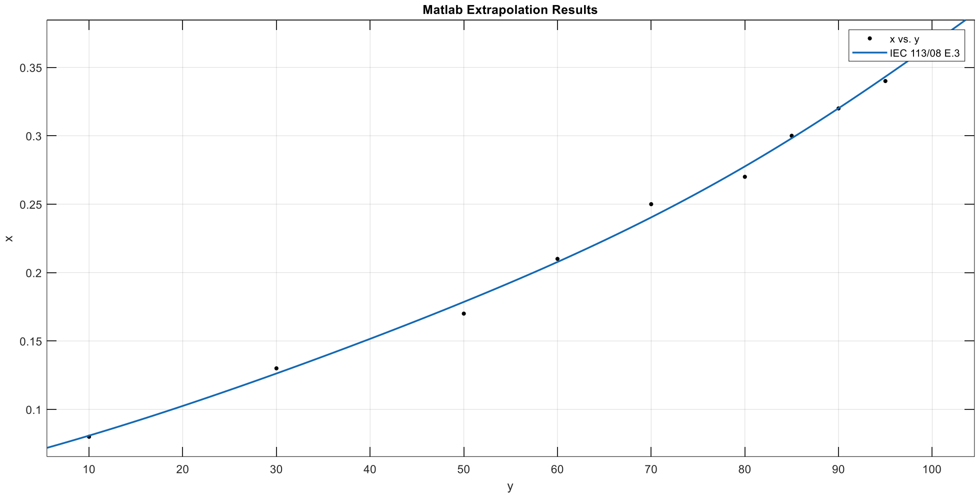


Figure E.3 – Shape factor curves for sinusoidal and triangular changes



Gaussian Result

General model Gauss3:

f(x) =

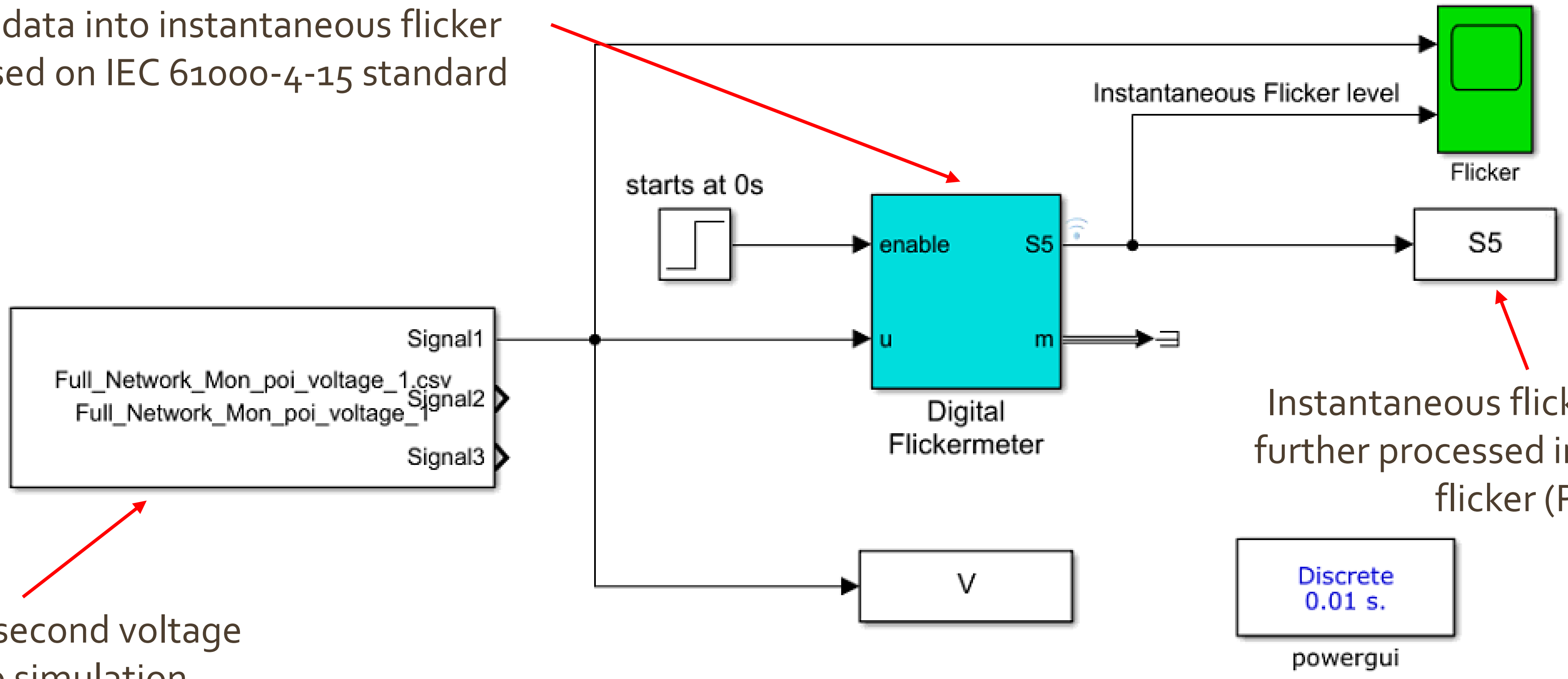
a1*exp(-((x-b1)/c1)^2) + a2*exp(-((x-b2)/c2)^2) +
a3*exp(-((x-b3)/c3)^2)

Coefficients (with 95% confidence bounds):

a1 = 0
b1 = 366.1
c1 = 32.36
a2 = -0.2181 (-1218, 1218)
b2 = 99.48 (-5.605e+04, 5.625e+04)
c2 = 57.76 (-5.521e+04, 5.532e+04)
a3 = 0.6687 (-1230, 1231)
b3 = 132.5 (-4.849e+04, 4.875e+04)
c3 = 89.01 (-4.486e+04, 4.504e+04)

Matlab Simulink Flicker Meter

Digital Flickermeter – process per second voltage data into instantaneous flicker level based on IEC 61000-4-15 standard



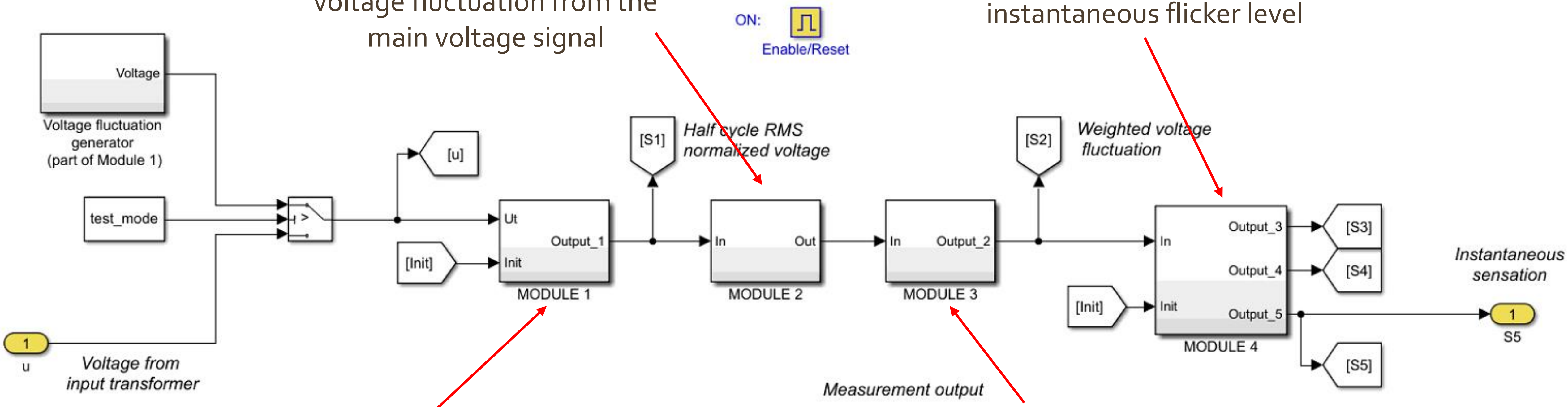
Instantaneous flicker level to be further processed into short term flicker (Pst)

Input the 1-second voltage data into simulation

Matlab Simulink Flicker Meter

Squaring demodulator – separate the low-frequency voltage fluctuation from the main voltage signal

Squaring multiplier and sliding mean filter – produce instantaneous flicker level



Input voltage adapter – scales the input half-cycle RMS value to an internal reference level

HP, LP, and weighting filter – filter out unwanted signals and weight the input signal according to the incandescent lamp eye-brain response

Matlab Simulink Flicker Meter

Statistical analysis code – process the instantaneous flicker level to produce short term flicker (Pst)

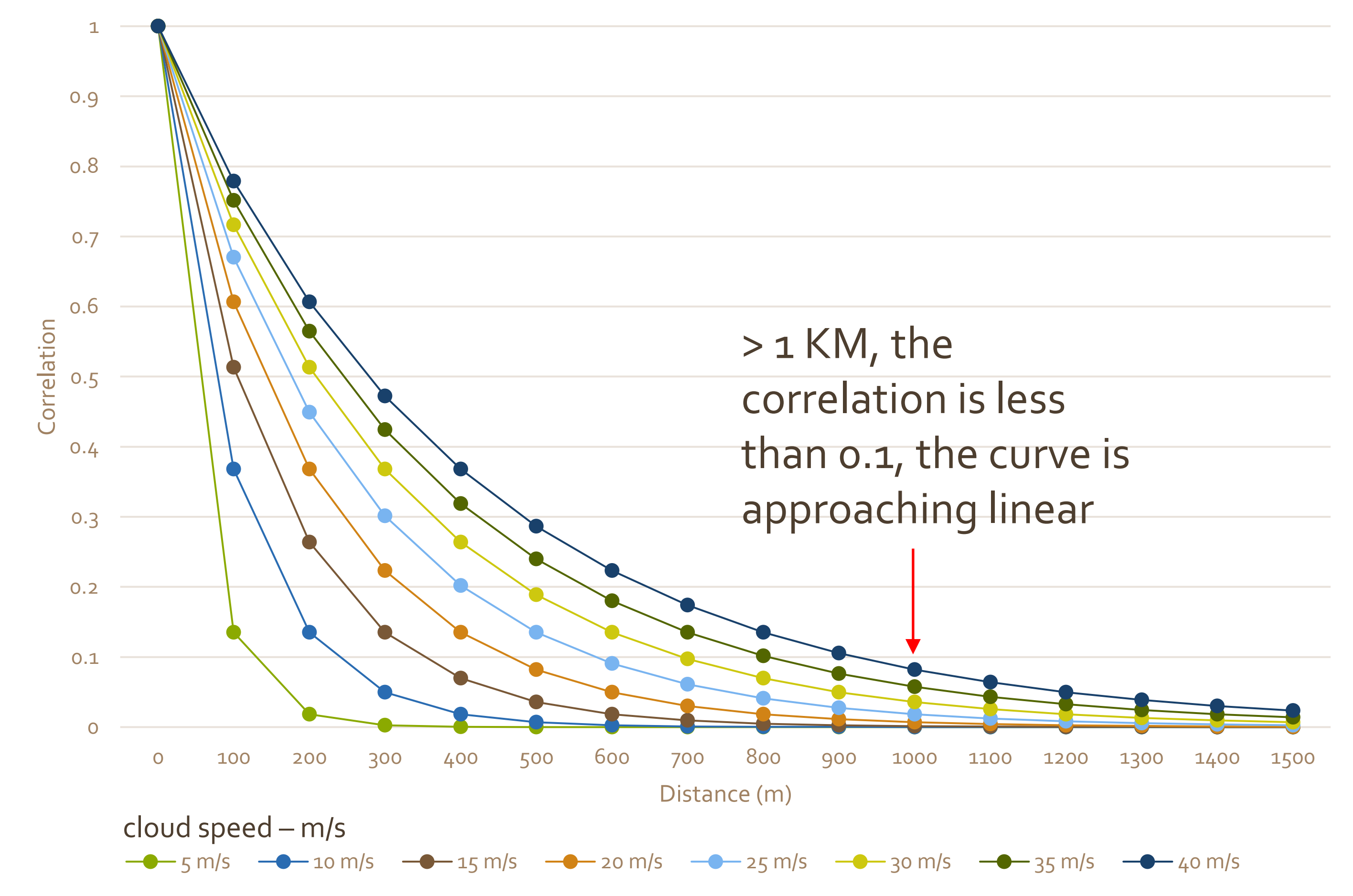
```
for i = 1:sec-600
    s = S5.signals.values((i-1)/st+1:(600/st)+(i-1)/st+1,:);
    NUMOF_CLASSES = 256;
    [bin_cnt, cpf.magnitude] = hist(s, NUMOF_CLASSES);
    cpf.cum_probability = 100 * (1 - cumsum(bin_cnt) / sum(bin_cnt));

    p_50s = mean([get_percentile(cpf, 30), get_percentile(cpf, 50), get_percentile(cpf, 80)]);
    p_10s = mean([get_percentile(cpf, 6), get_percentile(cpf, 8), ...
        get_percentile(cpf, 10), get_percentile(cpf, 13), get_percentile(cpf, 17)]);
    p_3s = mean([get_percentile(cpf, 2.2), get_percentile(cpf, 3), get_percentile(cpf, 4)]);
    p_1s = mean([get_percentile(cpf, 0.7), get_percentile(cpf, 1), get_percentile(cpf, 1.5)]);
    p_0_1 = get_percentile(cpf, 0.1);

    PstLM(:,turn) = sqrt(0.0314 * p_0_1 + 0.0525 * p_1s + 0.0657 * p_3s + ...
        0.28 * p_10s + 0.08 * p_50s);
end

Pst95_Matlab(:,turn) = prctile(PstLM(:,turn), 95);
Pst99_Matlab(:,turn) = prctile(PstLM(:,turn), 99);
```

Correlation Between Two Sites

- The correlated output determines how the cloud impacts at one side have the predictable effect on another site. The correlation factor:
  - Lower correlation as the distance between sites increases
  - Lower correlation as the cloud speed decreases
  - Decrease as the time interval decreases

- Low correlation means that variability on one site wouldn't affect the variability on the other sites. For example, PV sites that have a great distance between them would have a <u>low correlation</u>

- It is concluded that 1 KM can be used as the threshold (Sites with distance > 1 KM are uncorrelated)



Reference:

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- *A wavelet-based variability model (WVM) for Solar PV Power Plant, Matthew Lave, Jan Kleissl, Joshua S. Stein*